Strategy/False-name Proof Protocols for Combinatorial Multi-Attribute Procurement Auction

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Abstract

In this paper, we investigate a model of a combinatorial, procurement multi-attribute auction, in which each sales item is defined by several attributes called quality, the buyer is the auctioneer (e.g., a government), and the sellers are the bidders. Furthermore, there exist multiple items and both buyer and sellers can have arbitrary (e.g., substitutable/complementary) preferences on a bundle of items. Our goal is to develop a protocol that is strategy-proof for sellers. We first present a VCG-type protocol. As in a standard combinatorial auction, a VCG-type protocol is not false-name-proof, i.e., it is vulnerable against manipulations using multiple identifiers. Next, we show that any strategy-proof protocol in this model can be represented as a framework called Price-Oriented Rationing-Free (PORF) protocol, in which for each bidder, for each bundle of items, and for each quality, the payment for the bidder is determined independently of his own declaration, and the bidder can obtain a bundle that maximizes his utility independently of the allocations of other bidders. We develop a false-name-proof protocol in this model.

1. Introduction

Internet auctions have become an integral part of Electronic Commerce and a promising field for applying autonomous agents and multi-agent system technologies. Among various studies related to Internet auctions, those on combinatorial auctions have lately attracted considerable attention [10, 11] (an extensive survey is presented in [6]). Although conventional auctions sell a single item at a time, combinatorial auctions sell multiple items with interdependent values simultaneously and allow the bidders to bid on any combination of items. In a combinatorial auction, a bidder can express complementary/substitutable preferences over multiple bids. By taking into account complementary/substitutable preferences, we can increase the participants' utilities and the revenue of the seller.

However, the widespread research on auctions (including combinatorial auctions) deals mostly with models in which price is the unique strategic dimension. However, in many situations, it is necessary to conduct negotiations on multiple attributes of a deal. For example, in case of allocating tasks, the attributes of a deal may include starting time, ending deadline, accuracy level, etc. A service can be characterized by its quality, supply time, and risk involved, in case the service is not supplied eventually. Also, a product can be characterized by several attributes, such as size, weight, supply date, etc.

This problem becomes more complicated in case that there are multiple tasks, services, or products. For example, a task of constructing a large building can be divided into many subtasks. One constructor might be able to handle multiple subtasks, while another company is specialized to a particular subtask. In addition, since each constructor may contract processes under different conditions, i.e., their quality, appointed date, price and so on, the utility of the government may depend on these conditions in a complex fashion. A similar situation exists in case of an order of software development, etc.

In this paper, we investigate a model of a combinatorial, procurement multi-attribute auction, which can handle such situations. In this model, each sales item is defined by several attributes called quality, the buyer is the auctioneer

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(e.g., a government), and the sellers are the bidders. Furthermore, there exist multiple items and both buyer and sellers can have arbitrary (e.g., substitutable/complementary) preferences on a bundle of items. As far as the authors are aware, there has been no study that treats combinatorial, procurement multi-attribute auction so far.

In this paper, we assume that the preference/type of the buyer is known and set our goal to develop strategy-proof protocols for sellers. This assumption is natural in case of the procurement of the government, etc. Except for this assumption, our model is quite general. For example, the quality of a task can have arbitrary dimensions. Also, there is no restriction on the possible types of the cost function of a seller.

A protocol is strategy-proof if, for each bidder, declaring his[1] true evaluation values is a *dominant strategy*, i.e., an optimal strategy regardless of the actions of other bidders. In theory, the revelation principle states that in the design of an auction protocol, we can restrict our attention to strategy-proof protocols without loss of generality [9]. In other words, if a certain property (e.g., Pareto efficiency) can be achieved using some auction protocol in a dominant-strategy equilibrium, i.e., a combination of dominant strategies of bidders, the property can also be achieved using a strategy-proof auction protocol. A strategy-proof protocol is also practically useful for applying to Internet auctions. For example, if we use the first-price sealed-bid auction (which is not strategy-proof), the bidding prices must be securely concealed until the auction is closed. On the other hand, if we use a strategy-proof protocol, knowing the bidding prices of other bidders is useless; thus, such security issues become less critical.

We first present a VCG-type protocol. Next, we show that any strategy-proof protocol in this model can be represented as a framework called Price-Oriented Rationing-Free (PORF) protocol [13], in which for each bidder, for each bundle of items, and for each quality, the payment for the bidder is determined independently of his own declaration, and the bidder can obtain a bundle that maximizes his utility independently of the allocations of other bidders.

Electronic bidding via network becomes popular for procurement auctions. Since auction procedures can be efficiently carried out, it has been introduced very rapidly so far and it will be used more widely in the future. However, in regard to combinatorial auctions, the author pointed out the possibility of a new type of fraud called false-name bids, which utilizes the anonymity available in the Internet [15, 14]. False-name bids are bids submitted under fictitious names, e.g., multiple e-mail addresses. Such a dishonest action is very difficult to detect, since identifying each participant on the Internet is virtually impossible.

We say a protocol is *false-name-proof* if, for each bidder, declaring his/her true evaluation values using a single identifier (although the bidder can use multiple identifiers) is a dominant strategy. As for strategy-proof protocols, the revelation principle holds for false-name-proof protocols [15]. Thus, we can restrict our attention to false-name-proof protocols without loss of generality.

The VCG is not false-name-proof in case of combinatorial auctions, i.e., it is vulnerable against manipulations using multiple identifiers. This problem becomes a more serious one in the procurement auction. For example, let us consider the task allocation problem. The number of tasks is one hundred, there is no attribute except their prices, and there are two companies. When company 1 carries out all tasks, the cost is 100, and when company 2 does them, the cost is 110. When using the VCG, company 1 are assigned all tasks and the payment is 110. On the other hand, if company 1 makes 100 fictitious companies and each fictitious company bids one task with cost 1, then VCG allocates one task at the payment 11 to each fictitious company, respectively. In this case, the total payment is 1,100. In this paper, we also develop a false-name-proof protocol in this model.

The rest of this paper is organized as follows. We show the related works in Section 2. Then, we describe our auction model in Section 3. In Section 4, we develop a VCG type protocol to this problem. In Section 5, we show that any strategy-proof protocol in this model can be represented as PORF protocol. In Section 6, we develop a false-name-proof protocol. In Section 7, we discuss the proposed protocols, then in Section 8, we present our conclusions.

2. Related Works

So far, very little theoretical work has been conducted on multi-attribute auctions. One notable exception is the work of Che [2]. In [2], bidders bid on both price and quality, and bids are evaluated by a scoring rule designed by a buyer. In addition, first score and second score sealed bid auctions were proposed. However, in this work, the quality is assumed to be one-dimensional. Furthermore, multiple tasks cannot be treated.

Protocols and strategies of multi-attribute english auction were proposed in [4], then strategy with a deadline was studied in [5]. In these studies, processes of auctions are sequential, and they provide the automated bidder agents and their strategies. The value of the quality is extended in two dimensions. However, in this case also multiple tasks cannot be treated.

On the other hand, these works consider the incentive issues of the buyer, while we assume the type of the buyer is public. Also, these works propose non-direct revelation mechanisms, which require less exposure of private infor-

1 We use pronoun "he" to represent a seller/bidder and pronoun "she" to represent the buyer.

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mation than direct revelation protocols developed in this paper.

Bichler [1] carried out an experimental analysis of multi-attribute auctions, showing through experiments that the utility scores achieved in multi-attribute auctions were higher than those of single-attribute auctions.

3. Model

In this section, we describe the model of a combinatorial multi-attribute procurement auction.

- There exists a single buyer 0.
- There exists a set of sellers/bidders $N = \{1, 2, \ldots, n\}$.
- There exists a set of tasks $T = \{t_1, \ldots, t_m\}$.
- Each bidder i privately observes his type θ_i, which is drawn from a set Θ.
- For each task t_j, quality $q_j \in Q$ is defined.
- A possible allocation of tasks to bidders is represented as $\overrightarrow{B} = (B_1, \ldots, B_n)$, where $B_i \subseteq T$ and for $i \neq k$, $B_i \cap B_k = \emptyset$ holds.
- A profile of qualities is represented as $\overrightarrow{q} = (q_1, \ldots, q_m)$.
- For a quality profile $\overrightarrow{q}$ and bundle $B_i = \{t_{i,1}, t_{i,2}, \ldots\}$, we represent a projection of B_i onto $\overrightarrow{q}$ as $\overrightarrow{q}_{B_i} = (q_{t_{i,1}}, q_{t_{i,2}}, \ldots)$.
- The cost of bidder i when the allocation is B_i and the achieved quality profile is $\overrightarrow{q}_{B_i}$ is represented as $c(\theta_i, B_i, \overrightarrow{q}_{B_i})$. We assume c is normalized as $c(\theta_i, \emptyset, ()) = 0$.
- The gross utility of buyer 0 when the obtained quality profile is $\overrightarrow{q}$ is represented as $V(\overrightarrow{q})$.
- The payment from the buyer to each seller/bidder i is represented as p_i.
- We assume each participant's utility is quasi-linear, i.e., for each seller i, his utility is represented as $p_i - c(\theta_i, B_i, \overrightarrow{q}_{B_i})$. Also, for the buyer, her (net) utility is $V(\overrightarrow{q}) - \sum_{i \in N} p_i$.
- For an unallocated task t_j, we assume the quality of t_j is $q_0 \in Q$. V is normalized by $V(\overrightarrow{q}_0) = 0$ as $\overrightarrow{q}_0 = (q_0, q_0, \ldots, q_0)$.

Please note that although there is only one parameter q_j for representing the quality of task t_j, it does not mean our model can handle only one-dimensional quality,i.e., q_j can be a vector of multiple attributes.

In a traditional definition [8], an auction protocol is (dominant-strategy) *incentive compatible* (or *strategy-proof*) if declaring the true type/evaluation values is a dominant strategy for each bidder, i.e., an optimal strategy regardless of the actions of other bidders.

In this paper, we extend the traditional definition of incentive compatibility so that it can address false-name bid manipulations, i.e., we define that an auction protocol is (dominant-strategy) incentive compatible if declaring the true type *by using a single identifier* is a dominant strategy for each bidder. To distinguish between the traditional and extended definitions of incentive compatibility, we refer to the traditional definition as strategy-proof and to the extended definition as *false-name-proof*.

An auction protocol is *individually rational* if no bidder suffers any loss in a dominant-strategy equilibrium, i.e., the cost never exceeds the payment. In a private value auction, individual rationality is indispensable; no bidder wants to participate in an auction where he might be payed less money than what he spent to achieve the task. Therefore, in this paper, we restrict our attention to individually rational protocols. Also, we restrict our attention to deterministic protocols, which always obtain the same outcome for the same input.

We say an auction protocol is *Pareto efficient* when the sum of all participants' utilities (including that of the auctioneer), i.e., the social surplus, is maximized in a dominant-strategy equilibrium. In our model, the obtained social surplus is represented as $V(\overrightarrow{q}) - \sum_{i \in N} c(\theta_i, B_i, \overrightarrow{q}_{B_i})$. The author has proved that there exists no false-name-proof protocol that satisfies Pareto efficiency and individual rationality at the same time [15] in a combinatorial auction. Therefore, we need to sacrifice efficiency to some extent when false-name bids are possible.

An example of this model is shown below.

Example 1 *There are two bidders $N = \{1, 2\}$, two tasks $T = \{t_1, t_2\}$ and quality profile $\overrightarrow{q} = (q_1, q_2)$. In this case, we assume q_j is one-dimensional. For example, the cost functions of bidder 1 can be represented as follows.*

- $c(\theta_1, \{t_1\}, (q_1)) = \frac{1}{4}q_1$
- $c(\theta_1, \{t_2\}, (q_2)) = \frac{1}{2}q_2$
- $c(\theta_1, \{t_1, t_2\}, (q_1, q_2)) = \frac{1}{4}q_1 + \frac{1}{4}q_2$

Assume that $V(\overrightarrow{q}) = \sum_i \sqrt{q_i}$ and the cost of bidder 2 is always greater than that of bidder 1. When both t_1 and t_2 are allocated to the bidder 1 with $\overrightarrow{q} = (4, 4)$, then the cost of bidder 1 is $c(\theta_1, \{t_1, t_2\}, (4, 4)) = 2$. Social surplus is $V((4, 4)) - c(\theta_1, \{t_1, t_2\}, (4, 4)) = 2$.

In this case, social surplus is represented as $(\sqrt{q_1} - \frac{1}{4}q_1) + (\sqrt{q_2} - \frac{1}{4}q_2)$. Since this expression is maximized with the allocation described above, this allocation satisfies Pareto efficiency.

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4. VCG-type Protocol

4.1. Protocol Description

We can apply Vickrey-Clarke-Groves (VCG) mechanism [12, 7, 3] to the model described in Section 3.

Each bidder i declares his type $\tilde{\theta}_i$, which is not necessarily the true type θ_i.

Definition 1 (VCG)

- *Based on declared types, an allocation and a quality profile that maximizes social surplus are calculated as follows:*

$$(\overrightarrow{B}^*, \overrightarrow{q}^*) = \arg \max_{(\overrightarrow{B}, \overrightarrow{q})} V(\overrightarrow{q}) - \sum_{j \in N} c(\tilde{\theta_j}, B_j, \overrightarrow{q}_{B_j})$$

- *For i, payment p_i is defined as follows:*

$$p_i = [V(\overrightarrow{q}^*) - \sum_{j \neq i} c(\tilde{\theta_j}, B_j^*, \overrightarrow{q}^*_{B_j^*})] - [V(\overrightarrow{q}^{\sim i,*}) - \sum_{j \neq i} c(\tilde{\theta_j}, B_j^{\sim i,*}, \overrightarrow{q}^{\sim i,*}_{B_j^{\sim i,*}})]$$

$(\overrightarrow{B}^{\sim i,*}, \overrightarrow{q}^{\sim i,*})$ is an allocation and quality profile that maximizes social surplus except for i. More specifically, for an allocation that does not allocate a task to bidder i, i.e. $\overrightarrow{B}^{\sim i} = (B_1, \ldots, B_{i-1}, \emptyset, B_{i+1}, \ldots, B_n)$, $(\overrightarrow{B}^{\sim i,*}, \overrightarrow{q}^{\sim i,*})$ is defined as follows:

$$\arg \max_{(\overrightarrow{B}^{\sim i}, \overrightarrow{q}^{\sim i})} V(\overrightarrow{q}^{\sim i}) - \sum_{j \neq i} c(\tilde{\theta_j}, B_j^{\sim i}, \overrightarrow{q}^{\sim i}_{B_j^{\sim i}})$$

The proof that this protocol is strategy-proof is shown below. The utility of bidder i is written as follows.

$$\begin{aligned} p_i - c(\theta_i, B_i^*, \overrightarrow{q}^*_{B_i^*}) = \\ [V(\overrightarrow{q}^*) - \sum_{j \neq i} c(\tilde{\theta_j}, B_j^*, \overrightarrow{q}^*_{B_j^*}) - c(\theta_i, B_i^*, \overrightarrow{q}^*_{B_i^*})] \\ -[V(\overrightarrow{q}^{\sim i,*}) - \sum_{j \neq i} c(\tilde{\theta_j}, B_j^{\sim i,*}, \overrightarrow{q}^{\sim i,*}_{B_j^{\sim i,*}})] \end{aligned}$$

Because the second term of the equation is independent of declaration of bidder i, he can maximize his utility when he selects $\tilde{\theta_i}$ which maximizes first term. On the other hand, since $(\overrightarrow{B}^*, \overrightarrow{q}^*)$ maximizes $V(\overrightarrow{q}^*) - \sum_{j \in N} c(\tilde{\theta_j}, B_j^*, \overrightarrow{q}^*_{B_j^*})$, bidder i can maximize his utility if he declares $\tilde{\theta_i} = \theta_i$. Because the first term is greater than the second term, individual rationality holds for a seller.

Some examples of the VCG mechanism are shown below.

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Example 2 *We assume there are two bidders $N = \{1, 2\}$, two tasks $T = \{t_1, t_2\}$ and quality profile $\overrightarrow{q} = (q_1, q_2)$. In addition, we assume $V(\overrightarrow{q}) = V_1(q_1) + V_2(q_2)$ holds. Cost functions c_i when tasks are allocated to each bidder i are shown below.*

	t_1	t_2	t_1, t_2
c_1	$\frac{1}{4}q_1$	$\frac{1}{2}q_2$	$\frac{1}{4}q_1 + \frac{1}{2}q_2$
c_2	$\frac{1}{2}q_1$	$\frac{1}{4}q_2$	$\frac{1}{2}q_1 + \frac{1}{4}q_2$

We assume that $V_1(q_1) = \sqrt{q_1}, V_2(q_2) = \sqrt{q_2}$. In this case, $V(\overrightarrow{q}) - \sum_i c_i(q_i)$ is maximized when a task t_1 is allocated to bidder 1 and a task t_2 is allocated to bidder 2.

$$\begin{aligned} V(\overrightarrow{q}) - \sum_i c_i(q_i) &= V_1(q_1) + V_2(q_2) - c_1 - c_2 \\ &= \sqrt{q_1} + \sqrt{q_2} - \frac{1}{4}q_1 - \frac{1}{4}q_2 \\ &= (\sqrt{q_1} - \frac{1}{4}q_1) + (\sqrt{q_2} - \frac{1}{4}q_2) \end{aligned}$$

When the former part and the latter part of the equation are independently maximized, $V(\overrightarrow{q}) - \sum_i c_i(q_i)$ is maximized. Therefore, $q_1^* = 4, q_2^* = 4$.

The payment to bidder 1 is calculated as follows. When bidder 1 is absent, the best allocation is that both tasks are allocated to bidder 2.

$$\begin{aligned} V(\overrightarrow{q}) - \sum_i c_i(q_i) &= V_1(q_1) + V_2(q_2) - c_1 - c_2 \\ &= (\sqrt{q_1} - \frac{1}{2}q_1) + (\sqrt{q_2} - \frac{1}{4}q_2) \end{aligned}$$

In this case, $q_1^{\sim 1,*} = 1, q_2^{\sim 1,*} = 4$. Then the payment is $(\sqrt{4} + \sqrt{4} - 1) - (\sqrt{1} + \sqrt{4} - \frac{1}{2} - 1) = \frac{3}{2}$. The payment to bidder 2 is the same as bidder 1, $\frac{3}{2}$. The buyer's utility is $\sqrt{4} + \sqrt{4} - \frac{3}{2} - \frac{3}{2} = 1$, and the bidder's utility is $\frac{3}{2} - \frac{1}{4} \cdot 4 = \frac{1}{2}$.

Let us consider an example of the influence of fictitious bidding.

Example 3 *(A) Conditions are same as Example 2 except for cost functions, i.e. $T = \{t_1, t_2\}$, $N = \{1, 2\}$, $q = (q_1, q_2)$, and $V(q) = V_1(q_1) + V_2(q_2)$. Cost functions are assumed as follows.*

	t_1	t_2	t_1, t_2
c_1	$\frac{1}{4}q_1$	$\frac{1}{4}q_2$	$\frac{1}{4}q_1 + \frac{1}{4}q_2$
c_2	$\frac{1}{2}q_1$	$\frac{1}{2}q_2$	$\frac{1}{3}q_1 + \frac{1}{3}q_2$

We assume that $V_1(q_1) = \sqrt{q_1}$, $V_2(q_2) = \sqrt{q_2}$. When both task $t_1$and t_2 are allocated to bidder 1, $V(\overrightarrow{q}) - \sum_i c_i(q_i)$ is maximized. In this case, $q_1^* = 4$, $q_2^* = 4$, then the payment to bidder 1 is $2\frac{1}{2}$.

(B) We consider that bidder 1 create a fictitious bidder 3 and cost functions are set as follows.

	t_1	t_2	t_1, t_2
c_1	$\frac{1}{4}q_1$	$\frac{1}{2}q_2$	$\frac{1}{4}q_1 + \frac{1}{2}q_2$
c_2	$\frac{1}{2}q_1$	$\frac{1}{2}q_2$	$\frac{1}{3}q_1 + \frac{1}{3}q_2$
c_3	$\frac{1}{2}q_1$	$\frac{1}{4}q_2$	$\frac{1}{2}q_1 + \frac{1}{4}q_2$

In this case, the best allocation is that t_1 is allocated to bidder 1 and t_2 is allocated to bidder 3, and $q_1^* = 4$, $q_2^* = 4$. Then, the payments of bidder 1 and bidder 3 are both $1\frac{1}{2}$. However, since bidder 1 and bidder 3 are the same one, bidder 3 obtains 3. This is greater than the payment of bidder 1 in Example 3 (A).

4.2. Individual Rationality for Buyer

Unfortunately, this protocol cannot guarantee individual rationality for the buyer. Actually, even if the type of the buyer is known, there exists no protocol that is strategy-proof for sellers, individually rational both for sellers and a buyer, and can always achieve a Pareto efficient allocation.

We show a counter-example assuming such a protocol exists. There are two tasks $1, 2$ and two quality level q_0, q_1. q_1 means the task is performed and q_0 means the task is not performed. We assume $V((q_1, q_1)) = 10$, $V((q_1, q_0)) = V((q_0, q_1)) = V((q_0, q_0)) = 0$, i.e., these tasks are all-or-nothing for the buyer. Assume bidder 1 can execute task 1 with quality q_1 at cost 1, and bidder 2 can execute task 2 with quality q_1 at cost 1. In this case, since the protocol is Pareto efficient, it must assign task 1 to bidder 1 and task 2 bidder 2.

Let us represent the payment bidder 1 receives as p_1 and the payment of bidder 2 as p_2. In another situation, if the cost of bidder 1 is $9 - \epsilon$, where ϵ is a small amount, since the protocol is Pareto efficient, the protocol still assign task 1 to bidder 1 and task 2 to bidder 2. Let us represent the payment bidder 1 receives in this case as p_1'. Since the protocol is individually rational, the following condition must hold: $p_1' \geq 9 - \epsilon$. Since the protocol is strategy-proof, $p_1 = p_1'$ must hold. Therefore, $p_1 \geq 9 - \epsilon$. The same condition holds for p_2. As a result, $p_1 + p_2 \geq 18 - 2 \times \epsilon$ holds. However, this contradicts the assumption that the protocol is individually rational for the buyer.

4.3. Additive Case

Let us assume V is an additive form for the quality of each task, i.e., $V(\overrightarrow{q})$ can be represented as $V(\overrightarrow{q}) = V_1(q_1) + V_2(q_2) + \ldots + V_m(q_m)$. In other words, the gross utility of the buyer is the sum of the utilities for all tasks. Such a utility is quite common if these tasks are independent for the buyer.

In this case, the VCG-type protocol satisfies individual rationality. We assume V_i is normalized by $V_i(q_0) = 0$, where q_0 means the task is not performed. Also, we assume $V_B(\overrightarrow{q}_B) = \sum_{j \in B} V_j(q_j)$.

The payment bidder i receives when he is assigned a bundle of tasks B_i and achieve quality profile $\overrightarrow{q}_{B_i}$ is defined as follows:

$$p_i = [V(\overrightarrow{q}^*) - \sum_{j \neq i} c(\tilde{\theta_j}, B_j^*, \overrightarrow{q}^*_{B_j^*})] - [V(\overrightarrow{q}^{\sim i,*}) - \sum_{j \neq i} c(\tilde{\theta_j}, B_j^{\sim i,*}, \overrightarrow{q}^{\sim i,*}_{B_j^{\sim i,*}})]$$

Now, let us consider a case in which the task assignments and qualities except for bidder i are identical to $B^*, \overrightarrow{q}^*$, but tasks in B_i are not performed. In this case, the obtained social surplus becomes $V_{T \setminus B}(\overrightarrow{q}^*_{T \setminus B}) - \sum_{j \neq i} c(\tilde{\theta_j}, B_j^*, \overrightarrow{q}^*_{B_j^*})$. The second term of the definition of p_i, i.e., $V(\overrightarrow{q}^{\sim i,*}) - \sum_{j \neq i} c(\tilde{\theta_j}, B_j^{\sim i,*}, \overrightarrow{q}^{\sim i,*}_{B_j^{\sim i,*}})$ is obtained by optimizing the social surplus for all possible situations including the above-mentioned situation. Therefore, the following condition holds.

$$\begin{aligned} p_i &\leq [V(\overrightarrow{q}^*) - \sum_{j \neq i} c(\tilde{\theta_j}, B_j^*, \overrightarrow{q}^*_{B_j^*})] - \\ &\quad [V_{T \setminus B}(\overrightarrow{q}^*_{T \setminus B}) - \sum_{j \neq i} c(\tilde{\theta_j}, B_j^*, \overrightarrow{q}^*_{B_j^*})] \\ &= V_B(\overrightarrow{q}^*_B) \end{aligned}$$

As a result, $\sum_{i \in N} p_i \leq V(\overrightarrow{q}^*)$ holds, which means the protocol is individually rational.

If V does not have an additive form, we can design a modified protocol that is individually rational for the buyer by sacrificing efficiency. Let us assume V_i' is an arbitrary function that satisfies the following condition:

- For all $\overrightarrow{q}$, $V(\overrightarrow{q}) \geq \sum_i V_i'(q_i)$ holds.

Then, let us represent $\sum_i V_i'(q_i)$ as $V'(\overrightarrow{q})$. If we apply the VCG-type protocol assuming the buyer's gross utility is V' rather than V, as in the above discussion, we derive $\sum_{i \in N} p_i \leq V'(\overrightarrow{q}^*)$ holds. Since $V'(\overrightarrow{q}^*) \leq V(\overrightarrow{q}^*)$ holds, we can guarantee that this modified protocol satisfies individual rationality for the buyer. However, this protocol optimizes the social surplus using V' rather than the true gross utility of the buyer. Therefore, this protocol cannot guarantee Pareto efficiency.

Please note that this condition, i.e., V has an additive form, is a sufficient but not necessary condition that the VCG-type protocol is individually rational for the buyer. We expect that a condition similar to decreasing marginal utility [15] would be a necessary condition.

5. Extension of PORF Protocol

In this section, we show that any strategy-proof protocol in this model can be represented as a framework called

Price-Oriented Rationing-Free (PORF) protocol. For a standard combinatorial auction, it is shown that any strategy-proof protocol can be represented as a PORF protocol [13]. We then show that the PORF framework can be extended to the case of a combinatorial, multi-attribute procurement auction.

A PORF Protocol is defined as follows.

Definition 2 (PORF Protocol)

- *Each bidder i declares his type $\tilde{\theta}_i$, which is not necessarily the true type θ_i.*
- *For each bidder i, for each bundle $B \subseteq T$, and for each quality profile $\overrightarrow{q}_B$, the payment $p_{i,B,\overrightarrow{q}_B}$ is defined. This payment must be determined independently of i's declared type $\tilde{\theta}_i$, while it can be dependent on declared types of other bidders.*
- *We assume $p_{i,\emptyset,()} = 0$ holds.*
- *For bidder i, a bundle B^* is allocated and he is required to achieve the quality $\overrightarrow{q}_{B^*}$, where $(B^*, \overrightarrow{q}_{B^*}) = \arg\max_{(B,\overrightarrow{q}_B)} p_{i,B,\overrightarrow{q}_B} - c(\tilde{\theta}_i, B, \overrightarrow{q}_B)$. Bidder i receives $p_{i,B^*,\overrightarrow{q}_{B^*}}$. If there exist multiple bundles that maximize i's utility, one of these bundles is allocated.*
- *The result of the allocation satisfies* allocation-feasibility*, i.e., for two bidders i, j and bundles allocated to these bidders B_i^* and B_j^*, $B_i^* \cap B_j^* = \emptyset$ holds.*

It is straightforward to show that a PORF protocol is strategy-proof. For each bundle and quality profile, the payment that bidder i receives is determined independently of i's declared type, and he can perform the bundle with the quality so that his utility is maximized independently of the allocations of other bidders, i.e., the protocol is rationing-free.

On the other hand, in a PORF protocol, the payments must be determined appropriately to satisfy allocation-feasibility. The definition of a PORF protocol requires that if there exist multiple bundles that maximize i's utility, then one of these bundles must be allocated, but it does not specify exactly which bundle should be allocated. Therefore, if there exist multiple choices, the auctioneer can adjust the allocation of multiple bidders in order to satisfy allocation-feasibility.

Theorem 1 *Any strategy-proof combinatorial multi-attribute auction protocol can be described as a PORF protocol.*

This can be derived from lemma 1 and lemma 2 described below.

Lemma 1 *When types declared by the others are fixed, a strategy-proof protocol can be written as a function π. The argument of π is bidder i's declared type θ, and it returns bundles B, the qualities $\overrightarrow{q}_B$, and the payments p bidder i's receives, i.e., $\pi(\theta) = (B, \overrightarrow{q}_B, p)$.*

Assume for θ, θ', $\pi(\theta) = (B, \overrightarrow{q}_B, p)$ and $\pi(\theta') = (B, \overrightarrow{q}_B, p')$ hold, i.e., the protocol assigns the same bundle and quality profile. Then, $p = p'$ must hold.

Proof: We assume that $p < p'$ without loss of generality. When a bidder's true type is θ, if he declares false type θ', the payment increases though the bundle and the quality are the same. This is contrary to the assumption that π is strategy-proof. Therefore, the unique payment is determined, when π allocates the bundle B at quality $\overrightarrow{q}_B$ to bidder i. □

From Lemma 1, we can describe the payment of a strategy-proof protocol as $p(B, \overrightarrow{q}_B)$, i.e., a function of the allocation and quality profile.

Lemma 2 *A strategy-proof protocol π is described as a PORF protocol, that is, for any θ, $\pi(\theta) = (B, \overrightarrow{q}_B, p(B, \overrightarrow{q}_B))$, $(B, \overrightarrow{q}_B) = \arg\max_{(B,\overrightarrow{q}_B)} p(B, \overrightarrow{q}_B) - c(\theta, B, \overrightarrow{q}_B)$ holds, where $(B, \overrightarrow{q}_B, p(B, \overrightarrow{q}_B)) \in \bigcup_\theta \pi(\theta)$. In other words, the protocol allocates $(B, \overrightarrow{q}_B)$ which maximizes bidder i's utility based on the payment $p(B, \overrightarrow{q}_B)$, which is defined by each combination of B, $\overrightarrow{q}_B$.*

Proof: Assume that this does not hold, i.e., there exists $\pi(\theta') = (B', \overrightarrow{q}_{B'}, p')$ and $p(B, \overrightarrow{q}_B) - c(\theta, B, \overrightarrow{q}_B) < p(B', \overrightarrow{q}_{B'}) - c(\theta, B', \overrightarrow{q}_{B'})$ holds. In this case, if a bidder's true type is θ, when he declares his true type, his utility is $p(B, \overrightarrow{q}_B) - c(\theta, B, \overrightarrow{q}_B)$, and when he declares false type θ', his utility is $p(B', \overrightarrow{q}_{B'}) - c(\theta, B', \overrightarrow{q}_{B'})$. The latter utility is greater than the former. This contradicts the assumption that π is strategy-proof. □

6. False-name-proof Protocol

The VCG-type protocol described in Section 4 is strategy-proof and individually rational both for bidders and the buyer if V has an additive form. However, it is not false-name-proof protocol as described in Example 3. In this section, we develop a false-name-proof protocol in our model.

6.1. Additive Case

First, we consider the case that $V(\overrightarrow{q})$ has an additive form for the quality of each task, i.e,, $V(\overrightarrow{q})$ can be represented as $V(\overrightarrow{q}) = V_1(q_1) + \ldots + V_m(q_m)$. We denote $\sum_{j \in B} V_j(q_j)$ as $V_B(\overrightarrow{q}_B)$.

We determine the payment that bidder i receives if bundle B and quality profile $\overrightarrow{q}_B$ is assigned to bidder i as follows.

- First, we define $s_{i,B}$ as: $\max(0, \max_{B', j \neq i, \overrightarrow{q}_{B'}} (V_{B'}(\overrightarrow{q}_{B'}) - c(\theta_j, B', \overrightarrow{q}_{B'})))$, where B' represents an arbitrary bundle, which conflicts with B, i.e., $B \cap B' \neq \emptyset$.
- Then, $p_{i,B,\overrightarrow{q}_B}$ is defined as $V_B(\overrightarrow{q}_B) - s_{i,B}$.

Theorem 2 *In case that $p_{i,B,\overrightarrow{q}_B}$ is defined as above, the protocol satisfies allocation-feasibility.*

Proof: For each task t_k, let us select a bidder, a bundle and a quality profile $j^*, B^*, \overrightarrow{q}_{B^*}$ so that $V_B(\overrightarrow{q}_B) - c(\theta_j, B, \overrightarrow{q}_B)$ is maximized for all bundles that include t_k.

For the other bidder i, the payment is $V_{B'}(\overrightarrow{q}_{B'}) - [V_{B^*}(\overrightarrow{q}_{B^*}) - c(\theta_j, B^*, \overrightarrow{q}_{B^*})]$ when he carries out any bundle B' that includes t_k at $\overrightarrow{q}_{B'}$. If he chooses this bundle and quality profile, his utility is given as follows.

$$\begin{aligned} & V_{B'}(\overrightarrow{q}_{B'}) - [V_{B^*}(\overrightarrow{q}_{B^*}) - c(\theta_j, B^*, \overrightarrow{q}_{B^*})] \\ & -c(\theta_i, B', \overrightarrow{q}_{B'}) \\ = \ & [V_{B'}(\overrightarrow{q}_{B'}) - c(\theta_i, B', \overrightarrow{q}_{B'})] \\ & -[V_{B^*}(\overrightarrow{q}_{B^*}) - c(\theta_j, B^*, \overrightarrow{q}_{B^*})] \end{aligned}$$

Because of the condition of choosing B^*, etc., the second term is greater than the first term. Therefore, this utility is negative so bidder i won't choose this bundle. Therefore, allocation-feasibility holds. □

Next, we show that the protocol is also false-name-proof.

If bidder i is assigned a bundle $B = B1 \cup B2$ with quality profile $\overrightarrow{q}_B$, the payment is $V_B(\overrightarrow{q}_B) - s_{i,B}$.

If bidder i uses two identifiers (i' and i'') and is assigned $B1$ for i' and $B2$ for i'', the payment becomes as follows[2].

$$\begin{aligned} & V_{B1}(\overrightarrow{q}_{B1}) - s_{i,B1} + V_{B2}(\overrightarrow{q}_{B2}) - s_{i,B2} \\ = \ & V_{B1}(\overrightarrow{q}_{B1}) + V_{B2}(\overrightarrow{q}_{B2}) - [s_{i,B1} + s_{i,B2}] \\ = \ & V_B(\overrightarrow{q}_B) - [s_{i,B1} + s_{i,B2}] \end{aligned}$$

Since $s_{i,B} = \max(s_{i,B1}, s_{i,B2})$, $s_{i,B} \leq s_{i,B1} + s_{i,B2}$ holds. Therefore, if a bidder uses two identifiers and is assigned tasks separately, his payment becomes less. Thus, this protocol is false-name-proof.

Also, this protocol is individually rational for both bidders and the buyer. Since a bidder can always choose not to perform any task, his utility is at least 0. Also, for the buyer, $s_{i,B}$ is non-negative. Therefore, for any feasible allocation with quality profile $\overrightarrow{q}$, the sum of the payments is less than $V(\overrightarrow{q})$.

Example 4 *We assume there are two bidders $N = \{1, 2\}$, two tasks $T = \{t_1, t_2\}$ and quality profile $\overrightarrow{q} = (q_1, q_2)$. In addition, we assume $V(\overrightarrow{q}) = V_1(q_1) + V_2(q_2)$ and $V_i = \sqrt{q_i}$. Costs are shown below for when tasks are allocated to each bidder i.*

	bidder 1		bidder 2	
q_i	t_1	t_2	t_1	t_2
1	$\frac{1}{4}$	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{4}$
4	1	2	2	1

When a bidder has carried out both tasks, the costs are added.

Combinations of bundles of tasks are represented as $\{t_1, t_2\}$, $\{t_1\}$, $\{t_2\}$, $\emptyset$.

In the case that t_1 is allocated to bidder 1 and t_2 is allocated to bidder 2, the payments and the utilities of bidder 1 for each quality are shown below.

q_1	q_2	payment	utility
1	1	$-\frac{1}{2}$	$-\frac{3}{4}$
1	4	$\frac{1}{2}$	$\frac{1}{4}$
4	1	$\frac{1}{2}$	$-\frac{1}{2}$
4	4	$\frac{3}{2}$	$\frac{1}{2}$

In this case, the maximum utility of bidder 1 is $\frac{1}{2}$. For the other bundles, the maximum utilities are calculated in the same way. These are shown as follows.

task allocation of bidder 1	payment	maximum utility
t_1, t_2	$\frac{3}{2}$	0
t_1	$\frac{3}{2}$	$\frac{1}{2}$
t_2	0	$-\frac{1}{2}$
$\emptyset$	0	0

Therefore, the best allocation for bidder 1 is that he chooses only t_1, then he obtains the payment $\frac{3}{2}$ and the utility $\frac{1}{2}$.

For bidder 2, the best allocation is that he chooses only t_2 at the quality 4, then he obtains the payment $\frac{3}{2}$ and the utility $\frac{1}{2}$.

In this case, social surplus is 2.

Example 5 *Next, we consider the example of the same conditions as in Example 4, except for a table of costs.*

Costs are shown below, when tasks are allocated to each bidder i, respectively.

	bidder 1		bidder 2	
q_i	t_1	t_2	t_1	t_2
1	1	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$
4	4	2	2	2

The result of calculation of bidders' utilities is that bidder 1's utilities are always negative or 0, and the bundle which makes bidder 2's utility positive is the only one described below.

bundle	quality	utility
$\{t_1\}$	$\{1\}$	$\frac{1}{2}$

In this case, bidder 2's utility is $\frac{1}{2}$. Social surplus is $\frac{1}{2}$ and the buyer's utility is 0.

2 Strictly speaking, the payment becomes less because the declaration of i' can decrease the payment for i''.

6.2. Extension to General Case

In this subsection, we consider the case where V does not have an additive form. Let us assume $V'_i(q_i)$ is arbitrary function that satisfies the following condition.

- For all $\overrightarrow{q}$, $V(\overrightarrow{q}) \geq \sum_i V'_i(q)$ holds.

As in Section 6.1, we denote $\sum_{j \in B} V'_j(q_j)$ as $V_B(\overrightarrow{q}_B)$.

The discussion of Section 6.1 still holds for newly defined V'_i as long as the above condition holds. Therefore, this protocol satisfies allocation feasibility and false-name-proof. Also, this protocol is individually rational for both bidders and the buyer. For the buyer, for any feasible allocation with quality profile $\overrightarrow{q}$, the sum of the payments is less than $\sum_{j \in T} V'_j(q)$. Since $\sum_{j \in T} V'_j(q_j) \leq V(\overrightarrow{q})$, this protocol is individually rational for the buyer.

7. Discussions

We discuss the condition described in Section 4.3 and 6.2, i.e. $\sum_{j \in T} V'_i(q_i) \leq V(\overrightarrow{q})$. When V has an additive form, we can simply use V_i. Otherwise, we need to define V'_i that satisfies this condition.

Let as assume $V(\overrightarrow{q})$ is defined as $V(\overrightarrow{q}) = \max_{j \in T} V_j(q_j)$, i.e., tasks are substitutable for the buyer. If we define $V'_j(q_j)$ as $V'_j(q_j) = V_j(q_j)/|m|$, then the condition $\sum_{j \in T} V'_j(q_j) \leq V(\overrightarrow{q})$ is satisfied. For the false-name-proof protocol, we can use this V'. For the VCG-type protocol, even if we use V instead of V', the protocol satisfies individual rationality for the buyer.

On the other hand, let us assume $V(\overrightarrow{q})$ is defined as $V(\overrightarrow{q}) = \min_{j \in T} V_j(q_j)$, i.e., tasks are all-or-nothing. In this case, we need to choose $V'_j(q_j) = 0$ for all q_j, if we assume $V_j(q_0) = 0$, where q_0 represents that the task is not performed. This means no task can be assigned if we use V'_j. In this case, the VCG-type protocol cannot satisfy individual rationality for the buyer if we directly use V.

8. Conclusions

In this paper, we introduced a new model of a combinatorial procurement multi-attribute auction, in which each sales item (e.g. task) is defined by several attributes called quality. First, we presented a VCG-type protocol. Next, we showed that any strategy-proof protocol in the model can be represented as a framework called PORF protocol. Then, we developed a false-name-proof protocol in this framework.

As discussed in Section 7, our proposed protocols have limitations when the gross utility of the buyer does not have an additive form, especially in the case that it is all-or-nothing. Our future works include developing new protocols that can handle such situations. Also, we hope to develop a non-direct revelation protocols that require less exposure of private information.

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